VIII.5 Component Testing for Industrial Trucks and Early Market Applications

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End Date: Project continuation determined annually by DOE

FY 2011 Objectives

(1) Provide technical basis for the development of standards defining the use of steel (type 1) storage pressure vessels for gaseous hydrogen:
  - Compare fracture mechanics based design approach for fatigue assessment of pressure vessels for gaseous hydrogen to full-scale performance tests.
  - Generate performance test methods and data for fatigue assessment of full-scale pressure vessels with gaseous hydrogen.

(2) Codes and standards advocacy:
  - Participate in the standards development activities for gaseous hydrogen storage in pressure vessels, in particular Canadian Standards Association (CSA) and Society of Automotive Engineers (SAE) activities.

Technical Barriers

This project addresses technical barriers from the Codes and Standards section of the Fuel Cell Technologies 2007 Multi-Year Research Plan:

(F) Limited DOE Role in the Development of International Standards
(I) Conflicts between Domestic and International Standards
(N) Insufficient Technical Data to Revise Standards

Contribution to Achievement of DOE Codes and Standards Milestones

This project will contribute to achievement of the following DOE milestones from the Codes and Standards section of the Fuel Cell Technologies Program Multi-Year Research, Development and Demonstration Plan:

- **Milestone 21:** Completion of necessary codes and standards needed for the early commercialization and market entry of hydrogen energy technologies (4Q, 2012). This project enables the development and implementation of codes and standards by providing expertise and data on hydrogen compatibility of hydrogen pressure vessels.
- **Milestone 25:** Draft regulation for comprehensive hydrogen fuel cell vehicle requirements as a GTR approved (UN Global Technical Regulation). (4Q, 2010)

FY 2011 Accomplishments

- Built infrastructure for accelerated pressure cycling of hydrogen storage tanks.
- Fatigue crack growth testing of low-alloy steels extracted for pressure vessels shows engineering predictions to be conservative relative to performance testing of pressure vessels.
- Pressure cycling of two pressure vessel designs (T1 and T2 respectively):
  - T1 design: >47,000 cycles (and continuing three tanks as of July 2011).
  - T2 design: >26,000 cycles (and continuing one tank as of July 2011).
- Pressure cycling pressure vessels with engineered defects to quantify effects of existing flaws:
  - Four failures observed (stable through-wall cracks).
  - Greater number of cycles to failure than predictions.
- Procedures for pressure testing with gaseous hydrogen are being included in CSA Hydrogen Powered Industrial Truck (HPIT)1 and SAE J2579 working documents for performance testing.

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Introduction

Fatigue cracks can nucleate and grow in metals subjected to cyclic stress. The increment of crack growth per load cycle (da/dN) is a function of the driving force for fatigue cracking, which is called the applied stress intensity factor range (ΔK). Under conditions of stable fatigue crack growth, a simple empirical relationship can be used to describe fatigue crack growth in terms of the driving force: $da/dN = C(\Delta K)^m$, where C and m are experimentally determined constants.

Fatigue crack growth of a pressure vessel subjected to pressure cycling is enabled by the presence of manufacturing defects in the steel and accelerated by exposure to gaseous hydrogen. The latter characteristic is often referred to as “hydrogen embrittlement” and depends on the partial pressure of the gaseous hydrogen and the kinetics of hydrogen uptake into the steel. Consequently, the fatigue crack growth relationship is affected by variables such as hydrogen pressure, pressure-cycle frequency, pressure-time relationship (wave form), and temperature.

Although steel pressure vessels may be vulnerable to fatigue crack growth aided by hydrogen embrittlement, the industrial gas companies have used such pressure vessels for hydrogen transport and storage for decades. Typically, these pressure vessels are subjected to less than one pressure cycle per day (and in many cases less than one cycle per month), thus fatigue crack growth is generally not a concern. Pressure vessels for hydrogen storage in new applications such as those for lift trucks are anticipated to experience up to six pressure cycles per day, approaching an order of magnitude greater than the duty cycle of typical transportable industry gas pressure vessels.

Since the duty cycle for lift truck pressure vessels is outside the window of current experience, a methodology for determining the cycle life must be established. A deterministic engineering analysis for quantifying the progression of fatigue cracks is provided in the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (Section VIII, Division 3, Article KD-4) and extended to the specific case of high-pressure gaseous hydrogen in Article KD-10. This framework provides a method for conservatively estimating the fatigue cycle life of pressure vessels based on assessment of existing flaws in the pressure vessel. An alternate method has been proposed based on the measured performance of manufactured pressure vessels subjected to pressure cycling coupled with statistical assessment of the quality of the pressure vessels and desired cycle life. These two methods have been referred to as engineering analysis method and performance evaluation method respectively.

Approach

During this project, pressure vessels are being pressure cycled with gaseous hydrogen; the pressure vessels are identical to those in service for fuel cell forklift applications with gaseous hydrogen, with the exception that defects are engineered in some pressure vessels. The engineered defects were designed to simulate manufacturing flaws in the pressure vessels. Engineering analysis methods are being employed to compare the engineering analysis predictions with experimental results from the performance evaluation of full-scale pressure vessels. These efforts have required collaborations with fuel cell system integrators and pressure vessel manufacturers to obtain as-manufactured pressure vessels and produce pressure vessels with engineered defects for cycle testing, as well as develop a testing plan that reflects relevant engineering conditions, including pressure vessel designs, manufacturing flaws, and pressurization schedules. Additionally, direct participation in standards development activities has been a cornerstone of this effort, in particular with the technical advisory group for CSA’s HPIT1 and the subgroup drafting the language for the pressure vessel appendix in SAE J2579.

Results

Materials Testing

Sandia National Labs measured the rate of fatigue crack growth for three heats of 4130 steels in high-pressure gaseous hydrogen; testing coupons were extracted from pressure vessels supplied by the industrial partners (each heat of material came from a different vendor). Details of these experiments are given in reference [1]. The measured fatigue crack growth rates are shown in Figure 1, showing that all three materials performed nominally the same in gaseous hydrogen. ASME Boiler and Pressure Vessel Code (VIII-3) Article KD-10 requires the testing of three heats of a given steel to demonstrate that the effects of hydrogen are not sensitive to variations in the material’s microstructure or processing history. These measured fatigue crack growth rates are used to predict cycle life using engineering analysis methodologies that quantify crack growth through the vessel wall from manufacturing flaws in the pressure vessel.

Full-Scale Tank Testing

A system was designed and constructed to pressure cycle up to 10 full-scale tanks in parallel at a rate of approximately 250 discrete pressure cycles per day (approximately 5-minute pressure cycle time). The pressure vessels are cycled between 3.4 and 43.8 MPa, with an approximately 2-minute pressure ramp rate, 2-minute hold time at maximum pressure, 30-second depressurization rate,

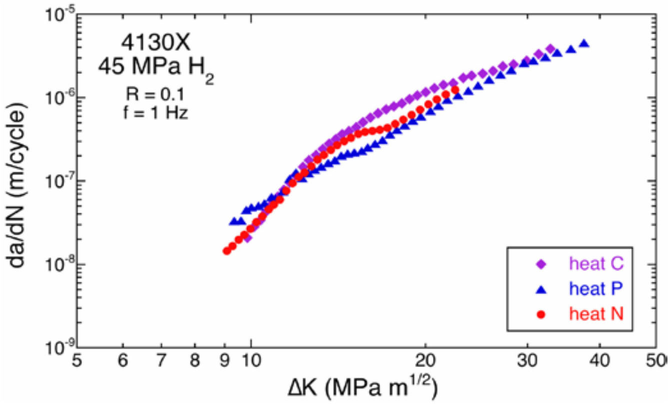

FIGURE 1. Fatigue Crack Growth Rates for three Heats of 4130X Steels (taken from reference [2])

and 30-second hold at minimum pressure. Details of the system, experimental procedures, and additional explanation of results are given in reference [2]. At the time of writing, pressure vessels have cycled for as many as 47,000 cycles without failure, although not all pressure vessels have experienced this number of cycles. Pressure vessels with engineered defects have been subjected to fewer cycles and four vessels have failed after as few as 8,000 cycles. Figure 2 shows the number of cycles that many of the pressure vessels have experienced as a function of the initial defect size for those pressure vessels with engineered defects. Also shown in this figure are the estimates of the cycle life assuming the engineered defects began propagating after the first pressure cycle. Clearly, these estimates underestimate the cycle life. Generally, there are two components to fatigue life, crack initiation and crack propagation. The engineering predictions are based on crack propagation only, since there is no broadly accepted way to account for crack initiation.

Leak-before-burst was observed for each of the four pressure vessel failures. This is an important observation because larger safety factors are generally applied when burst is a probable failure mode. Additionally, postmortem analysis suggests that the engineered defects form cracks that propagate with a semicircular profile (Figure 3), although as the crack depth reaches the full thickness of the vessel the shape again changes (Figure 4). This is also an important observation if shown to be generally true. Cracks with larger aspect ratios (such as the aspect ratio of the engineered defects) propagate at higher rates because the driving force is greater for a "long" crack compared to a "short" crack of the same depth.

These results are currently being discussed in the technical advisory committee for CSA HPIT1. The testing procedures are also being considered in SAE J2579.

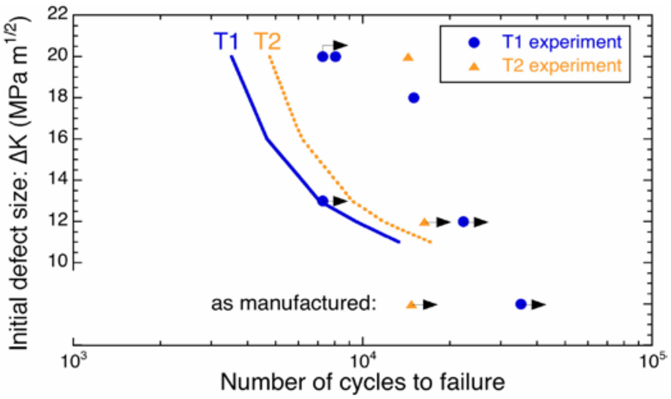

FIGURE 2. The number of cycles to failure in the cycled pressure vessels are given by symbols; arrows indicate that the pressure vessel is still cycling at the time of writing. The curves represent the estiamted cycles to propgate the initial defect to a through-wall crack (taken from reference [2]).

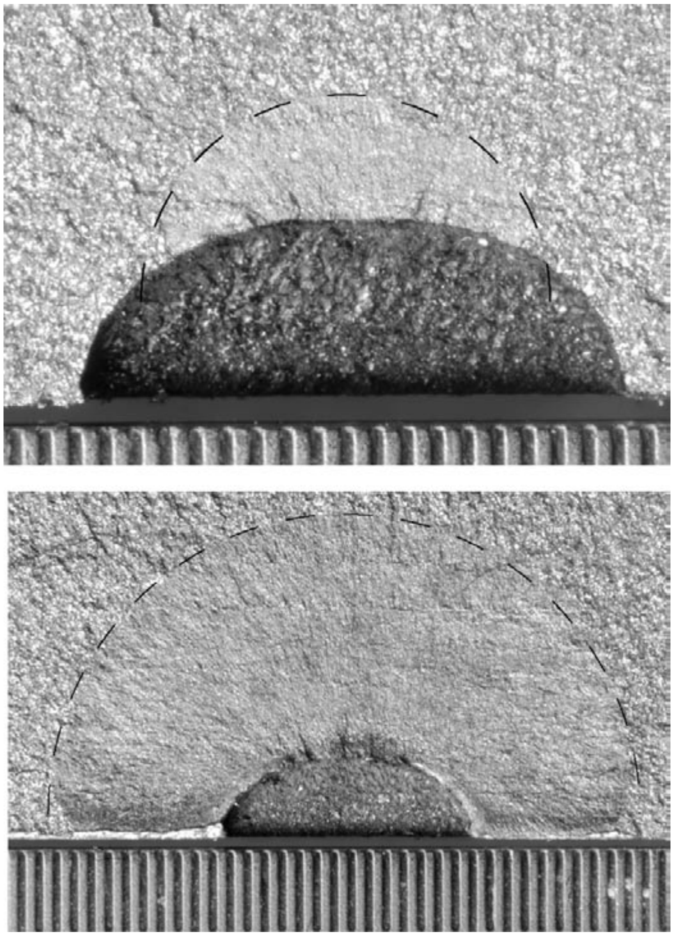

FIGURE 3. Crack extension from engineering defects that did not extend through the thickness of the pressure vessel have a semicircular profile.

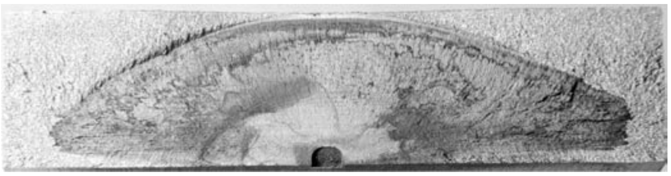

FIGURE 4. Through-wall cracks associated with the engineering defects do not have a semicircular crack profile.

Conclusions and Future Directions

- Commercial pressure vessels being used for hydrogen storage on forklifts have been subjected to more than 47,000 pressure cycles with gaseous hydrogen (between pressure of 3.4 and 43.8 MPa):
  - Primary aim of the remainder of project is to cycle tanks until they fail or reach 50,000 cycles.
- Fatigue crack growth assessment of engineered defects in these pressure vessels using engineering analysis appears to be conservative:

  - Post-mortem analysis is being used to refine predictions and interpret failure process.
- Code language based on the test methods developed in this study are being drafted as part of CSA HPIT1 and SAE J2579 for performance based tests:
  - Results are being shared with committees as they are generated.
- Leak-before-burst was observed in all failures.

References and FY 2011 Publications/Presentations

1. "Fracture and Fatigue Tolerant Steel Pressure Vessels for Gaseous Hydrogen", K. Nibur, C. San Marchi, and B. Somerday, *Proceedings of the ASME 2010 Pressure Vessels & Piping Division / K-PVP Conference*, Bellevue, Washington, July 18–22, 2010.

2. "Pressure Cycling of Type 1 Pressure Vessels with Gaseous Hydrogen", C. San Marchi, D.E. Dedrick, P. Van Blarigan, B.P. Somerday, K.A. Nibur, 4th International Conference on Hydrogen Safety (ICHS4), 12–14 September 2011, San Francisco CA.

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